

Transformer-Based Voltage Regulators with Flexible TLVR Structure for Extremely Fast Dynamic Response

Xingxuan Huang, Senior Applications Engineer,
Xinyu Liang, Senior Manager, Product Applications, and
Chuan Shi, Staff Applications Engineer

Abstract

An extremely fast dynamic response is highly desirable in voltage regulators (VRs) for various applications requiring high current up to thousands of amperes. This article presents transformer-based VRs with a trans-inductor voltage regulator (TLVR) structure designed to achieve an extremely fast response during load transients. Overcoming the drawbacks of traditional TLVR structure, transformer-based VRs with TLVR structure feature great design flexibility and extremely fast transient response, which results in smaller output capacitance and solution size, and lower system cost. Detailed experimental results and a case study are provided to demonstrate the comprehensive benefits of transformer-based VRs with TLVR structure.

Introduction

Nowadays multiphase VRs play an increasingly important role as they are used to power a wide range of microprocessors, such as CPUs, GPUs, and ASICs. In recent years, the power demand for these microprocessors has been increasing drastically, especially in telecom and some emerging applications, such as crypto mining and autonomous driving systems. Microprocessors are thereby requiring higher current with a higher slew rate. Hence, VRs are required to have a faster dynamic response during load transients to satisfy the output voltage ripple requirements. From the perspective of system size, an extremely fast dynamic response is highly attractive to reduce the required output capacitance and shrink the size of output capacitors. Moreover, smaller output capacitance and fewer output capacitors benefit the system cost. This article will present a transformer-based VR solution with a TLVR structure designed to realize extremely fast load transient response and substantially shrink the size and cost of output capacitors. When introducing TLVR structure in transformer-based VR solutions, traditional challenges of TLVR structure can be easily tackled.

Design and implementation details will be provided, and comprehensive benefits will be demonstrated with a case study based on practical applications. It also should be noted that the design and implementation details in this article are currently patent pending.

TLVR structure is an effective implementation to accelerate dynamic response during the load transients of multiphase VRs.^{12,3} As shown in Figure 1, the TLVR structure leverages TLVR inductors to replace the output inductors in traditional multiphase VRs. A TLVR inductor can be regarded as a 1:1 transformer that possesses a primary winding and a secondary winding. The coupling of all TLVR inductors is realized by connecting the secondary windings of all TLVR inductors. The current in the secondary side of TLVR inductors, I_{Lr} , is determined by the control signals of all different phases. Because of the coupling effect, the output current of all phases can ramp up or down at the same time once the duty cycle of one phase of the VR changes to respond to the load transient. That is why the TLVR structure can achieve excellent load transient performance.

Transformer-Based VRs

Transformer-based VRs have been competitive power solutions for various microprocessors. Equipped with a step-down transformer, transformer-based VRs feature a high and flexible step-down ratio, a simple and compact structure, and high efficiency. Compared to transformerless multiphase VRs, transformer-based VRs allow much higher input voltage and hence open a whole new world for simplifying VR design and achieving higher efficiency.

Figure 2 shows the circuit diagram of one representative example of the transformer-based VR. The VR circuit features a step-down transformer with two secondary windings and a current doubler structure on the secondary side. More secondary windings can be designed to achieve higher output current and

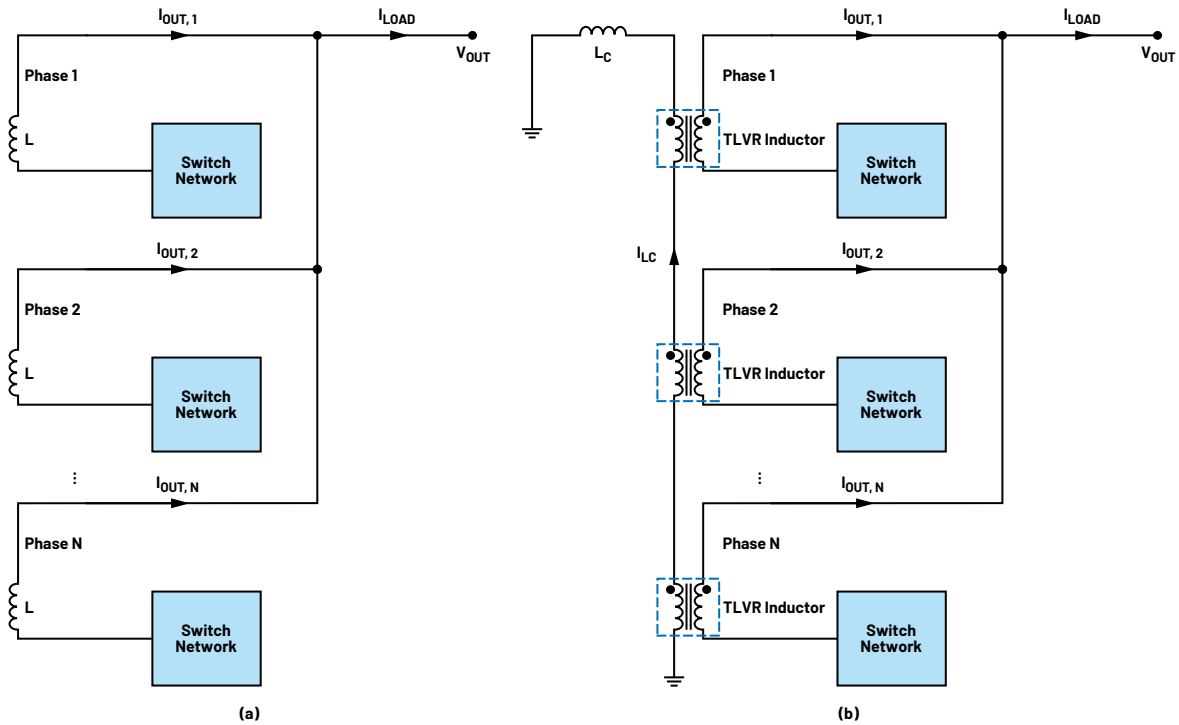


Figure 1. (a) A circuit diagram of a traditional multiphase VR without TLVR structure and (b) a circuit diagram of a multiphase VR with TLVR structure.

power density, and no additional control signals are needed on the secondary side. With proper control circuits and strategy, multiple example VR circuits in Figure 2 can be easily connected in parallel to provide the required current for a wide range of high performance microprocessors. Therefore, the VR circuit shown in Figure 2 is used as an example throughout this article.

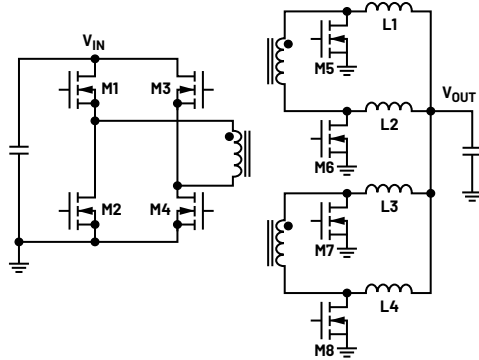


Figure 2. A circuit diagram of one transformer-based VR example.

Benefits of TLVR Structure in Transformer-Based VRs

It is well demonstrated that the TLVR structure can significantly accelerate the dynamic response of the VRs without any step-down transformer during load transients. However, such superior dynamic performance is introduced together with numerous challenges.^{1,2,3} Without any step-down transformer, these transformerless VRs typically operate with low duty cycle and high voltage applied in both the primary and secondary sides of TLVR inductors. The high voltage-second in the secondary side of TLVR inductors results in a high circulating current in the secondary side of TLVR inductors and additional power loss during the steady state operation. Hence, as can be seen in Figure 1b, an additional inductor L_C should be added to limit the circulating current in the secondary windings of TLVR inductors.¹ The additional inductor further increases the system loss and cost.

The challenges brought by the TLVR structure can be smoothly tackled when introducing the TLVR structure in transformer-based VRs. By combining the TLVR structure with the step-down transformer, the drawbacks of the TLVR structure become much less significant due to the high step-down ratio of the main transformer. Meanwhile, the extremely fast dynamic response can still be achieved, as the coupling effect pushes the current of all phases to respond simultaneously during load transients. Because of the step-down transformer, the voltage applied to the TLVR inductors becomes much lower, leading to lower inductor loss. The inductance of the additional inductor required in the secondary side of the TLVR inductors can be much lower. In fact, by leveraging the parasitic inductance, the additional inductor can be eliminated, as well as the additional loss and cost brought by the inductor. In addition, the insulation issue associated with the TLVR inductors and the additional inductor is no longer a concern.

Transformer-Based VRs with Flexible TLVR Structure

In transformer-based VRs with TLVR structure, all output inductors in the circuit are replaced by the TLVR inductors. Moreover, two types of implementations can be realized when applying the TLVR structure in transformer-based VRs, which offers great flexibility when implementing this structure. Figure 3 shows the circuit diagrams of the two types of implementations using the example of two VR modules shown in Figure 2 connected in parallel. The implementation in Figure 3a is called series connection since all the secondary windings of TLVR inductors are connected in series. The other implementation shown in Figure 3b is called a series-parallel connection. In Module 1, the secondary windings of L11 and L12 are connected in series before they are connected in parallel with the series connection of the secondary windings of L13 and L14. Such a connection of secondary windings of TLVR inductors in Module 1 is finally connected in series with the counterpart connection in Module 2, as shown in Figure 3b. Similarly, two implementations with TLVR structures in Figure 3 can be realized when more than two transformer-based VR modules are connected in parallel.

Enhanced flexibility in design and implementation does not increase the control complexity. The same control scheme is applied for the two implementations of the transformer-based VR with TLVR structure. Here, the control scheme for the transformer-based VR with three modules in parallel is introduced as an example. Phase shift is inserted between control signals for different VR modules. The inserted phase shift between Module 1 and Module 2 is 60° , and a phase shift of 60° is inserted between control signals for Module 2 and Module 3. If there are N modules in parallel, the inserted phase shift between two adjacent modules is $180/N^\circ$.

Based on the proposed control scheme, the voltage applied to all TLVR inductors can be derived. Figure 4 summarizes the voltage waveforms of all TLVR inductors in the transformer-based VR with two modules connected in parallel. Since the two types of implementations in Figure 3 have the same control signal, the inductor voltage waveforms are also the same. It can also be observed that L11 and L13 have the same voltage waveform, which is the case for L12 and L14 as well. These inductor voltage waveforms effectively explain why the series-parallel connection in Figure 3b is legitimate. The current in the secondary side of TLVR inductors, I_{sec} , has a high frequency ripple at $4 \times$ switching frequency of MOSFETs in the primary side of the main step-down transformer. With N ($N > 2$) modules connected in

parallel, the current ripple of I_{sec} will be at a higher frequency ($2N \times$ the switching frequency), and the magnitude of I_{sec} can be further reduced. Therefore, the proposed control scheme with phase shift can not only reduce the output voltage ripple, but also effectively suppress the ripple of I_{sec} and hence the conduction loss in the secondary side of TLVR inductors.

Also, no additional inductor is required in the transformer-based VR with TLVR structure. The additional cost and loss brought by the additional inductor are eliminated as well, which substantially benefits the system's efficiency and cost. Because of the high transformer step-down ratio (small n), the voltage of TLVR inductors is reduced substantially compared to the transformerless VR with TLVR structure. Hence, it is not necessary to introduce the additional compensation inductor L_c in the secondary side of the TLVR inductor to suppress the current ripple. Detailed information about the TLVR inductor voltage can be seen in Figure 4. In this case, the parasitic inductance in the circuit and the leakage inductance of TLVR inductors play a critical role in shaping the current in the secondary side of TLVR inductors, I_{sec} . To further improve the dynamic performance during the load transient, it is important to reduce the leakage inductance and the parasitic inductance in the secondary side of TLVR inductors.

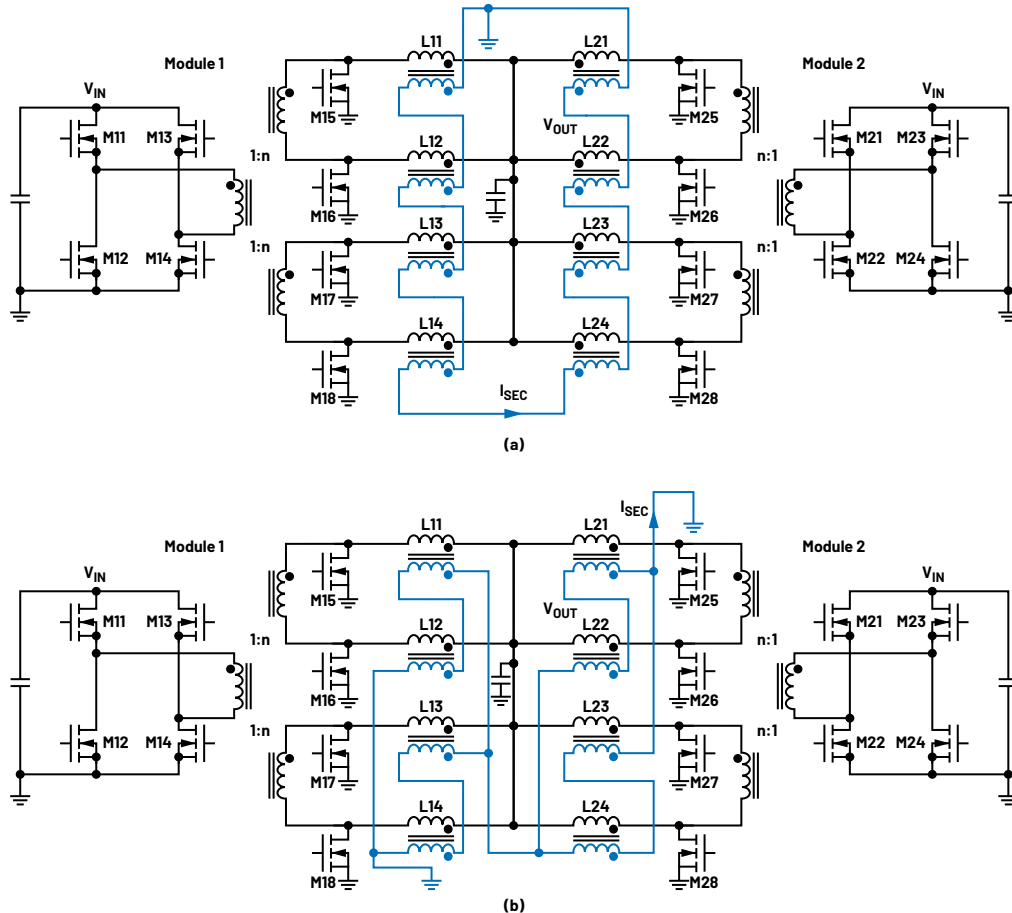


Figure 3. Two implementations of two parallel transformer-based VR modules with TLVR structure: (a) a series connection and (b) a series-parallel connection.

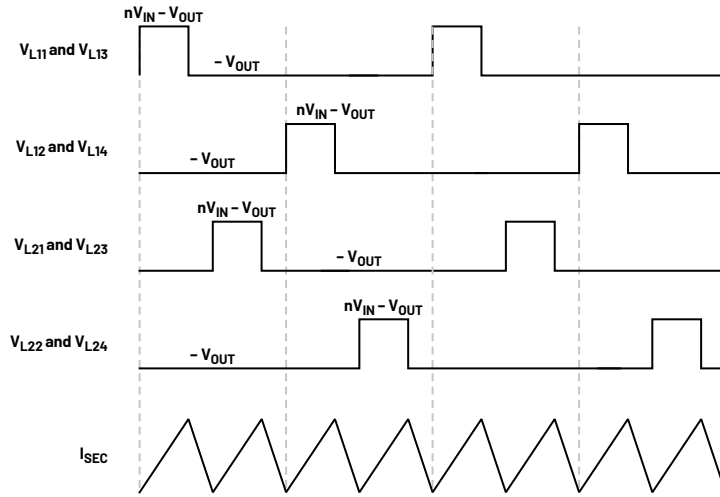


Figure 4. Waveforms of voltage and secondary current of TLVR inductors in transformer-based VR modules with TLVR structure (two modules in parallel).

Prototypes and Experimental Results

Both implementations of the transformer-based VR module with TLVR structure are designed and built, including the series connection version and the series-parallel connection version. Figure 5a displays the 3D model of a typical TLVR inductor. The built module prototype can be seen in Figure 5b. Both versions have the same size as their counterpart without TLVR structure. In other words, adopting TLVR inductors to realize the TLVR structure does not increase the VR module size, no matter whether a series connection or series-parallel connection is implemented.

The extremely fast load transient performance of the transformer-based VR with TLVR structure has been successfully demonstrated with the built prototypes. The experimental setup consists of two VR modules operating in parallel, as shown in Figure 5b. No additional inductor is installed in the secondary side of TLVR inductors. The load transient is between 20 A and 170 A with a slew rate of 125 A/ μ s. The excellent load transient response of the transformer-based VR

with TLVR structure is clearly illustrated in the baseline comparison shown in Figure 6, in which the series-parallel connection version is used as an example. To make a fair comparison, the case without the TLVR structure is realized by disconnecting the connection in the secondary side of TLVR inductors. As the load current steps up from 20 A to 170 A, the transformer-based VR with TLVR structure can regulate the output voltage more quickly with a much lower peak-to-peak voltage ripple.

An extremely fast load transient response is achieved in the transformer-based VR with TLVR structure, after conducting further improvement. Detailed transient waveforms can be seen in Figure 7. Under the same transient from 20 A to 170 A, the peak-to-peak output voltage ripple is only 23.7 mV, thanks to the extremely fast response brought by the TLVR structure. Adopting the TLVR structure substantially accelerates the dynamic response and hence reduces the peak-to-peak output voltage ripple by 62%. The measured high control bandwidth of 115 kHz also demonstrated the extremely fast load transient response enabled by the TLVR structure. A detailed comparison is summarized in Table 1.

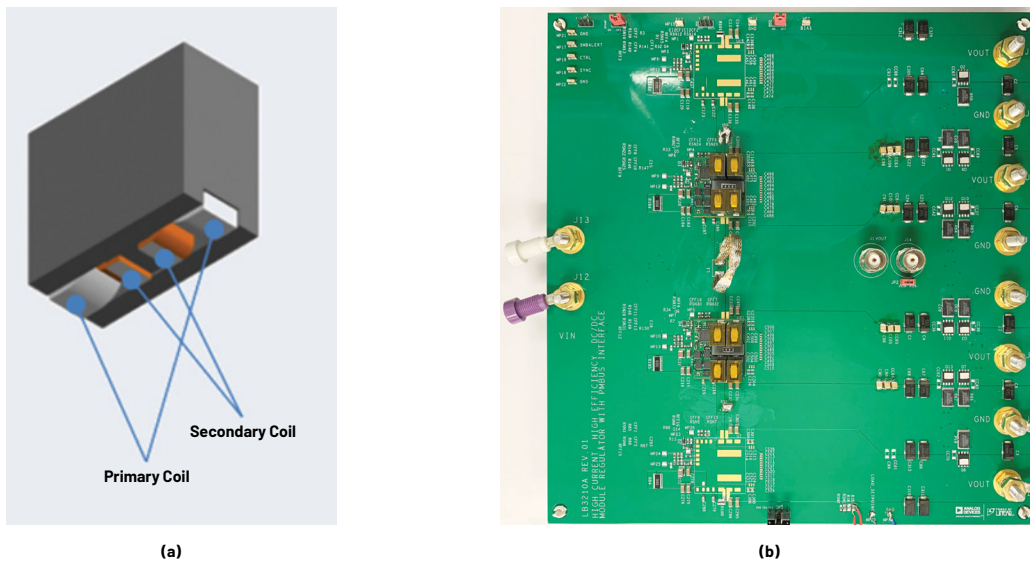


Figure 5. (a) A 3D model of TLVR inductor and (b) two transformer-based VR prototypes with TLVR structure in parallel on a demo board.

Table 1. Comparison of Dynamic Response Between a Transformer-Based VR with TLVR Structure and Without TLVR Structure

Structure	With TLVR Structure	Without TLVR Structure
Output Capacitance	15.2 mF	15.2 mF
Voltage Ripple (pk-pk)	23.7 mV	62 mV
Control Bandwidth	115 kHz	45 kHz
Phase Margin	69°	40.7°

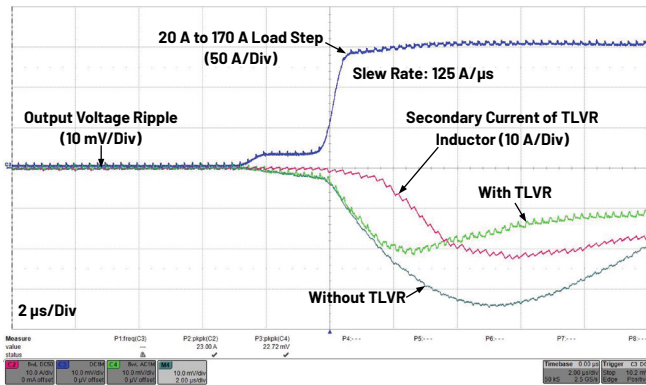


Figure 6. Comparison of load transient response of a transformer-based VR with TLVR structure and without TLVR structure.

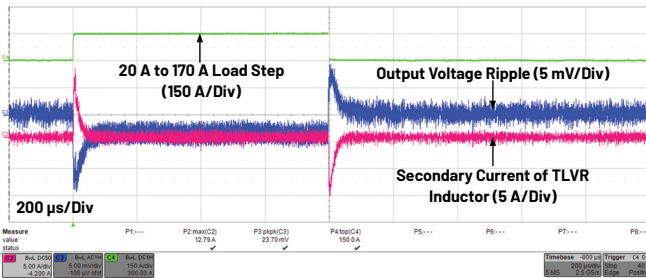


Figure 7. Extremely fast load transient response of a transformer-based VR with TLVR structure.

Case Study

To further showcase the benefits of combining transformer-based VRs with the TLVR structure, this section introduces a case study of transformer-based VR based on specifications from practical applications. Both transformer-based VR solutions with and without TLVR structures are implemented and tested to provide a 0.825 V/540 A rail. Details of specifications and test results are summarized in Table 2. With comparable phase margin and gain margin, the transformer-based VR solution with TLVR structure achieves 61% higher control bandwidth than the VR solution without TLVR structure. Thus, the extremely fast transient enabled by the TLVR structure is demonstrated again, as shown in Figure 8. The peak-to-peak output voltage ripple is only 40.92 mV, lower than 5% of the 0.825 V output voltage.

With 39% output capacitance saved, the VR solution with the TLVR structure still realizes a much lower peak-to-peak voltage ripple compared to the VR solution without the TLVR structure. Thus, the number of output capacitors is reduced by 27%, resulting in a tremendous decrease in system solution size. Also, the cost of output capacitors can be cut by 43%, thanks to the extremely fast transient response enabled by the TLVR structure.

Generally, transformer-based VR with TLVR structure featuring extremely fast dynamic response can effectively reduce the output capacitance, while still maintaining low output voltage ripple during fast load transients. In addition, no additional inductor is required in transformer-based VRs with TLVR structure. Therefore, transformer-based VR solutions with TLVR structure can not only significantly reduce the total solution size but also result in a substantial reduction in solution cost, especially the cost of output capacitors. Two implementations available for use further bring the benefit of great flexibility, and meanwhile the control complexity is not increased.

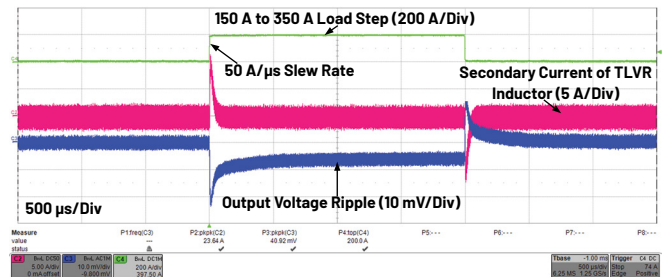


Figure 8. An extremely fast load transient response of a transformer-based VR with TLVR structure under 150 A to 350 A load transient (three VR modules in parallel).

Table 2. A Case Study of Transformer-Based VR Solution Based on Specifications from a Customer

Structure	VR Solution with TLVR Structure	VR Solution Without TLVR Structure
Output Current	540 A	540 A
Output Voltage	0.825 V	0.825 V
Number of VR Modules	Three in parallel	Three in parallel
Switching Frequency	550 kHz	550 kHz
Voltage Ripple (pk-pk)	40.92 mV	61.15 mV
Control Bandwidth	55 kHz	34.2 kHz
Phase Margin/ Gain Margin	78.8°/9.9 dB	65.5°/10.4 dB
Total Output Capacitance	24.88 mF	40.92 mF
Number of Output Capacitors	74	101
Cost of Output Capacitors	\$9.5	\$16.75

Summary

VR solutions for microprocessors are required to have accelerated dynamic response as microprocessors consume higher current with a higher slew rate in a wide range of applications. This article introduces the transformer-based VRs with TLVR structure to achieve extremely fast dynamic response during load transients of microprocessors. By combining transformer-based VRs with TLVR structure, the traditional challenges of TLVR structure can be easily tackled because of the large step-down ratio of the main transformer. Excessive loss in TLVR inductors can be significantly reduced, and no additional compensation inductor is required, leading to lower loss and cost. Moreover, two types of implementations can be adopted when implementing TLVR structure in transformer-based VRs, which provides great flexibility in design and implementation. Both implementations can cover numerous VR modules in parallel with the same control scheme. The experimental results prove that both implementations

can achieve extremely fast load transient response than their counterparts without TLVR structure, with 2.56× control bandwidth and 62% lower peak-to-peak voltage ripple. A detailed case study further presents the comprehensive benefits of transformer-based VRs with TLVR structure in solution size and cost.

References

- ¹“Fast Multi-phase Trans-Inductor Voltage Regulator.” *Technical Disclosure Commons*, May 2019.
- ²Ming Xu, Yucheng Ying, Qiang Li, and Fred C. Lee. “Novel Coupled-Inductor Multi-phase VRs.” *IEEE APEC*, February 2007.
- ³Shreyankh Krishnamurthy, David Wiest, and Yosef Zhou. “Trans-Inductor Voltage Regulator (TLVR): Circuit Operation, Power Magnetic Construction, Efficiency and Cost Trade-Offs.” *PCIM Europe*, May 2022.



About the Author

Xingxuan Huang is a senior applications engineer in Analog Devices CA, U.S.A., focusing on power products. He received his master's and Ph.D. degrees in electrical engineering from the University of Tennessee, Knoxville, in 2019 and 2021, respectively, with concentration on power electronics.



About the Author

Yinyu Liang is the applications engineering manager in the Industrial and Multimarket Group at Analog Devices focusing on power products. He received his Ph.D. degree in electrical engineering in 2018 from North Carolina State University and he started his career at ADI in 2019 after graduation.



About the Author

Chuan Shi is a staff applications engineer in Analog Devices CA, U.S.A. He received his Ph.D. degree in electrical engineering (with distinguished honor) from the University of Maryland, College Park, MD, U.S.A. His expertise is on modeling, analysis, design, and control of power electronic converters for automotive, industrial, and communication applications.



AHEAD OF WHAT'S POSSIBLE™

For regional headquarters, sales, and distributors or to contact customer service and technical support, visit analog.com/contact.

Ask our ADI technology experts tough questions, browse FAQs, or join a conversation at the EngineerZone Online Support Community. Visit ez.analog.com.

©2023 Analog Devices, Inc. All rights reserved. Trademarks and registered trademarks are the property of their respective owners.

VISIT [ANALOG.COM](https://analog.com)